# *Design and Fabrication of $Nb_3Sn$ Cos($\theta$) Dipole Models & Mirror Magnets*

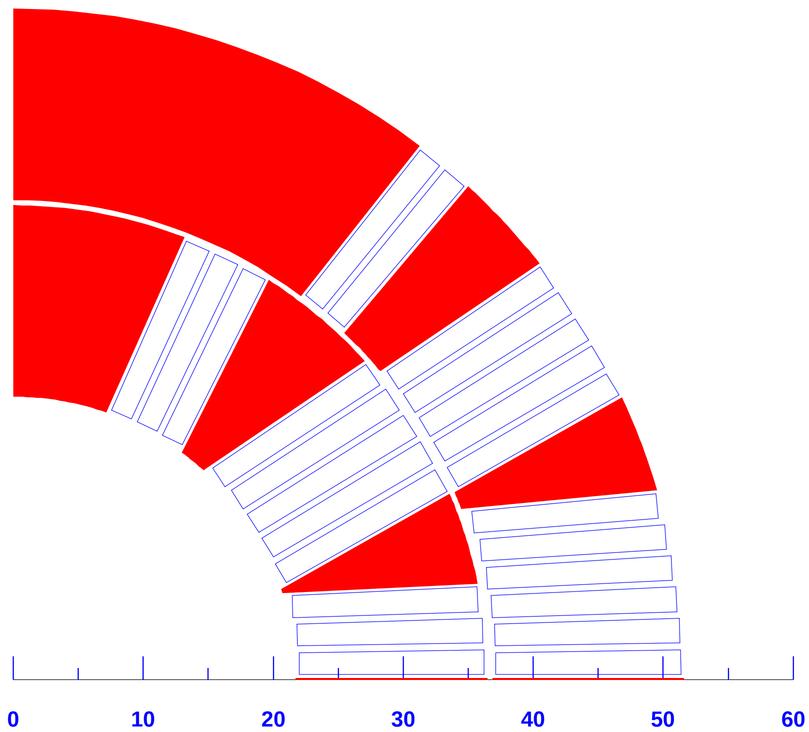
**Deepak Chichili**

SC Magnets
at Fermilab

# Outline

- **Magnet Design Overview**
  - **Magnetic Design**
  - **Mechanical Design**
- **Magnet Technology Overview**
  - **Dipole Model Fabrication**
  - **Mirror Magnet Fabrication**
  - **Data Analysis**
- **Current Status, HFDM-03 & beyond**
  - **Fabrication Schedule**

# Design Overview: Magnetic Design




- Magnet bore diameter: 43.5 mm
- Number of Turns: 48
- Strand: $Nb_3Sn$, $\phi$ 1.00 mm,
- Cable: N=28, 1.80 x 14.24 mm,
  Keystone Angle = 0.92
- $B_{max}$ = 12 T @ $J_c$ = 2000 A/mm$^2$
- $I_{max}$ = 22 kA
- Inductance = 1.29 mH/m
- Stored Energy = 310 kJ/m
- Insulation thickness: 250 $\mu$m

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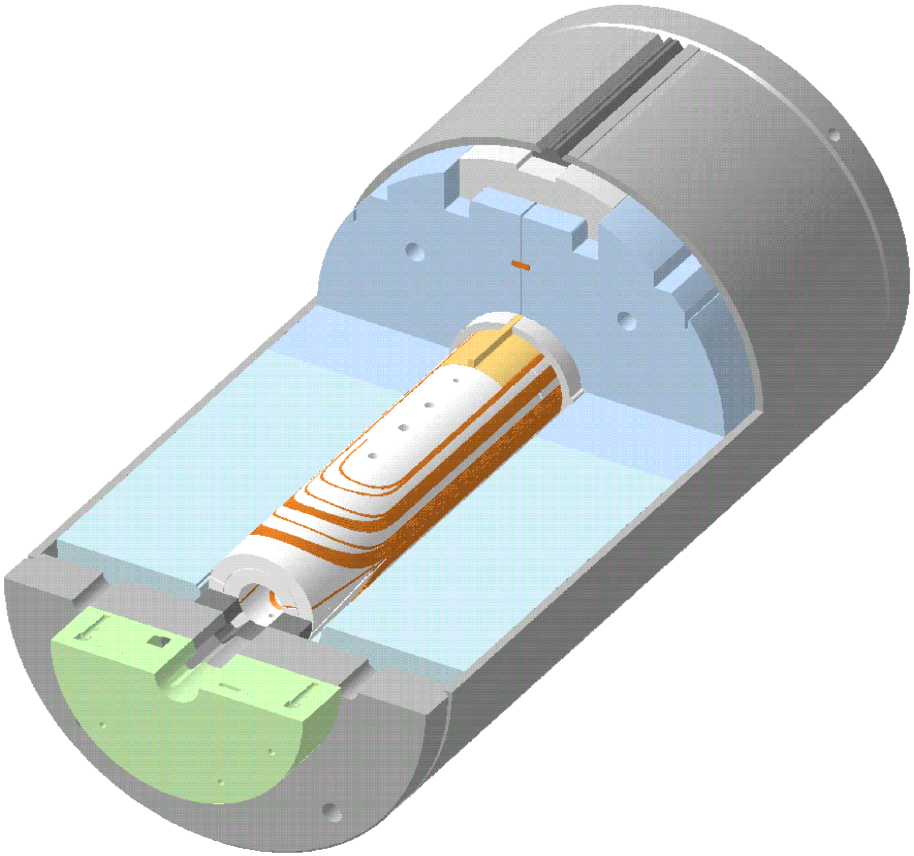
# Design Overview: Mechanical Support Structure



**DESIGN FEATURES:**

- **Wind and React approach**
- **Ceramic Insulation with Ceramic Binder**
- **No Interlayer Splice**
- **Spacers instead of Collars**
- **The gap between the two iron yoke halves remain open**
- **Coil prestress provided by both aluminum clamps and Skin**

# Magnet Technology Overview

- **Fabrication Steps (HFDA-01 through HFDA-04)**
  - **End-Part Design and Fabrication**
  - **Cable Insulation**
  - **Coil Winding and Curing**
  - **Coil Reaction**
  - **Splice Joints**
  - **Coil Impregnation**
  - **Yoking and Skinning**

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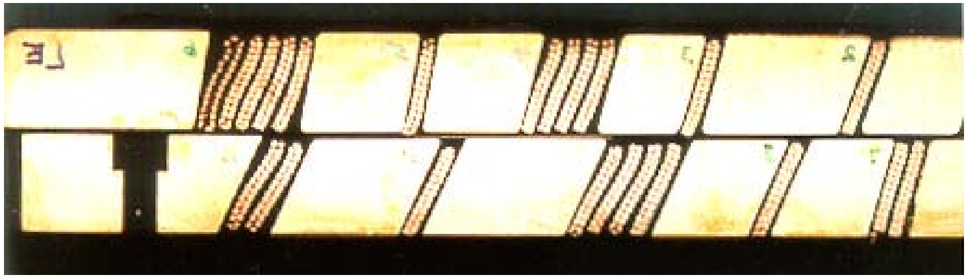
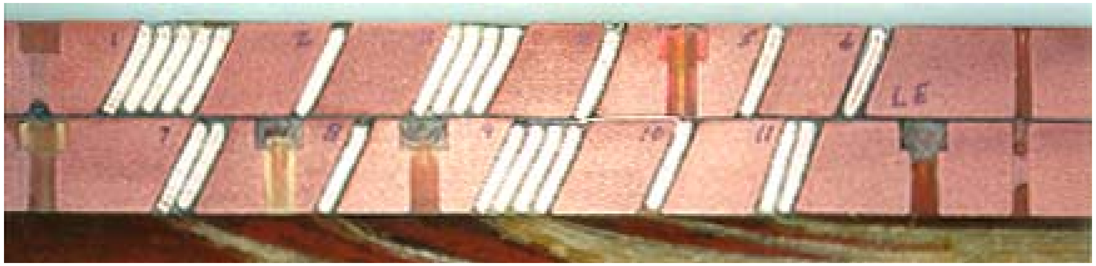
# End-Part Design

- The design of End-parts were optimized using the program BEND. Two iterations were performed,

First Generation End-Parts



Second Generation End-Parts



# End-Part Fabrication

- **Different manufacturing techniques were investigated to reduce the cost of the fabrication of end-parts**
  - **Laser Sintered parts with quick turn-around time were used to optimize the end-part design**
  - **Five Axis Water Jet Machining was used for manufacturing the end-parts from HFDA-02 magnet onwards.**

**Water Jet Machined Part**

| Manufacturing Technology | Cost for 4 Sets | Cost Per Part* | Machining Time, min |
|---|---|---|---|
| Conventional | 32,000 | 380 | 60 – 120 |
| Water Jet | 14,000 | 167 | 10 – 15 |
| Laser Sintered | 3,500 (for 1 set) | 167 | Complete set is done in one pass |

* Both conventional and water jet machining involves additional material costs

# Cable Insulation Process

- Both S-2 Fiberglass and Ceramic Tape have been used for cable insulation
- The in-organic binder is first applied to an already insulated cable by passing through wet rollers. The wet insulated cable is then cured at 80 ºC for 30 min.
- Upon winding, the coil is cured at 150 ºC for 30 min under pressure. The inorganic binder turns into a bonding agent which provides a rigid shape to the coil
- This scheme offers the following three advantages -
  - Restoration of tape strength after initial binder application
  - Possibility of assembling cured coils prior to heat-treatment
  - Easiness of cured coil handling

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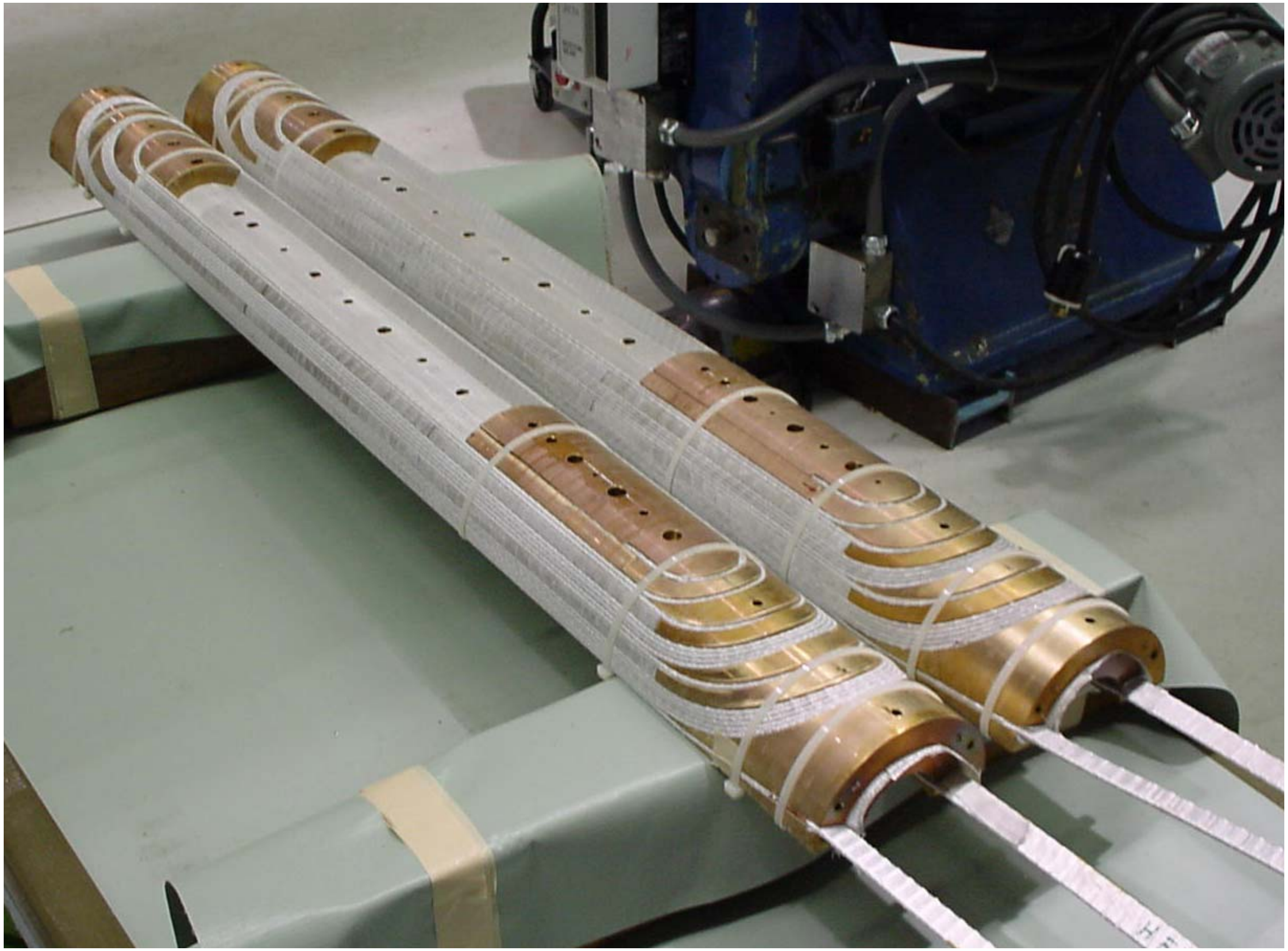
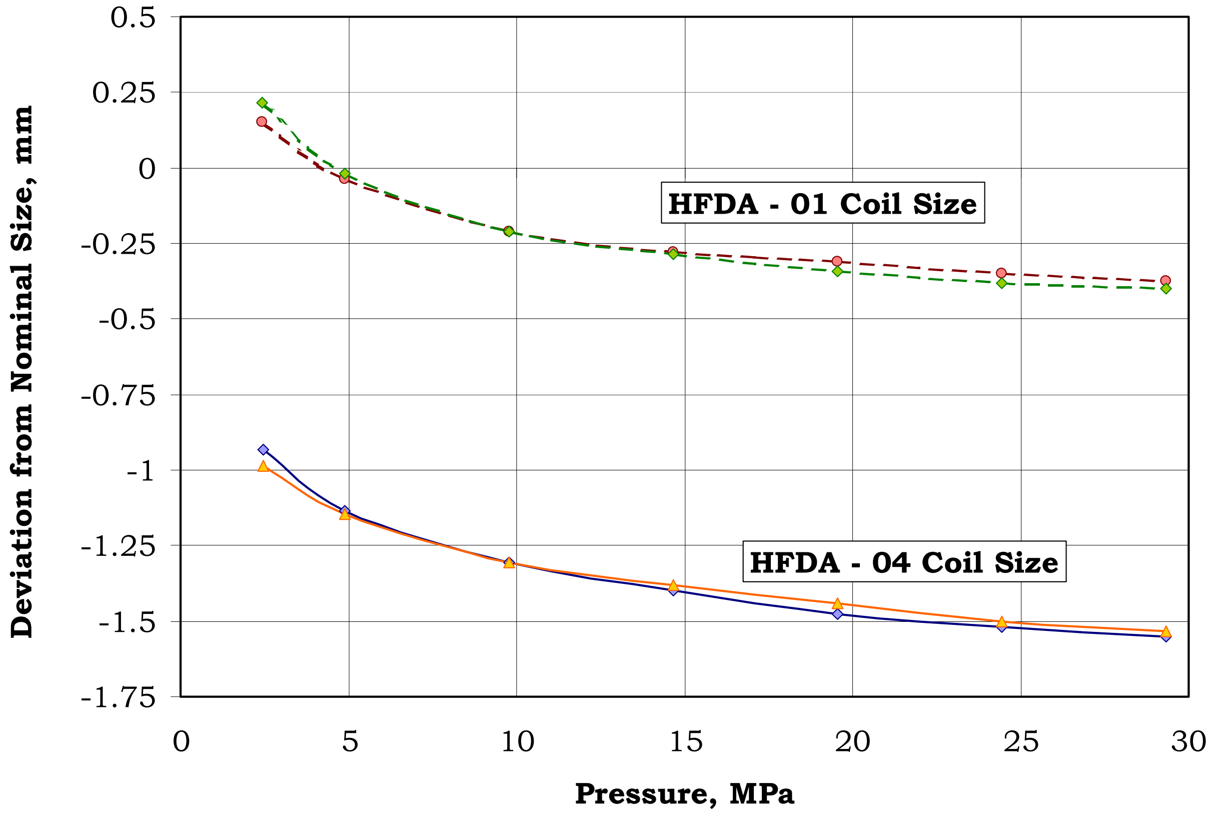
# Cured Half Coils

**Two half coils ready to be reacted…**



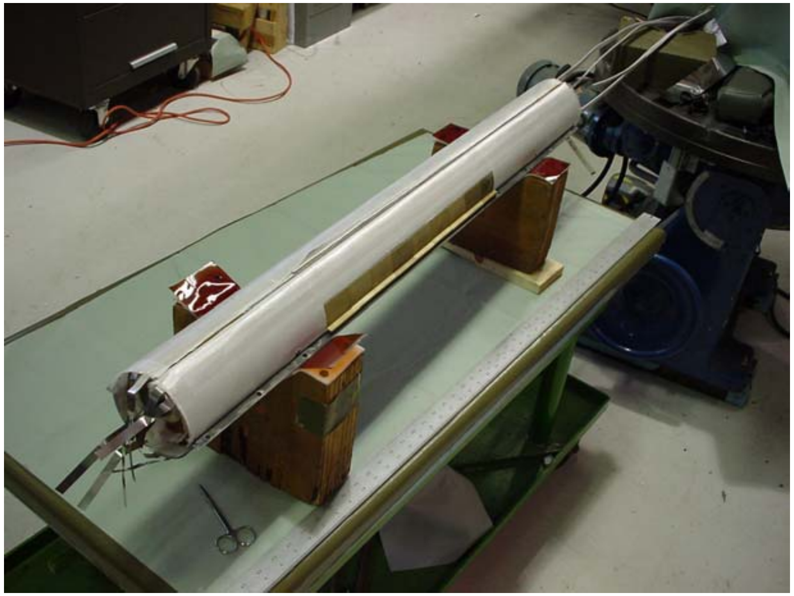
# Coil Azimuthal Size Measurements



# Coil Assembly

## Ground Insulation with Quench Protection Heaters

## Coils Assembled with Ground Insulation



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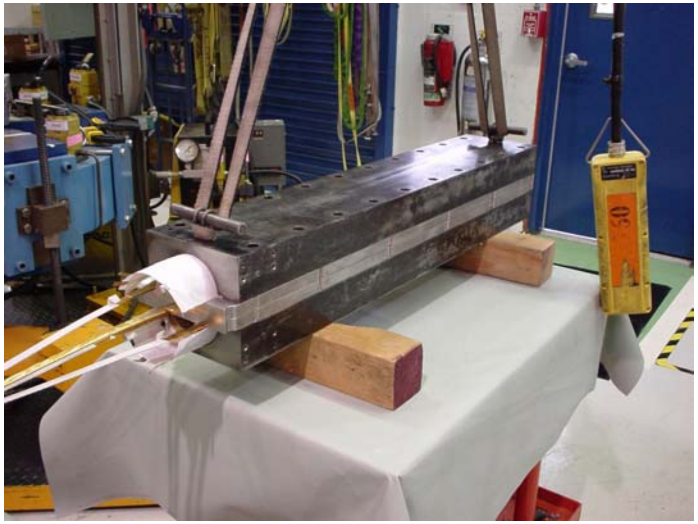
# Coil Reaction

## ❖ Reaction Fixture

- **In order to control the coil mid-plane and to have the option of splicing each half-coil separately, the reaction fixture was modified for HFDA-04**
  - Each half coil was held in one half of the reaction fixture using mid-plane spacers.

HFDA-01 through HFDA-03



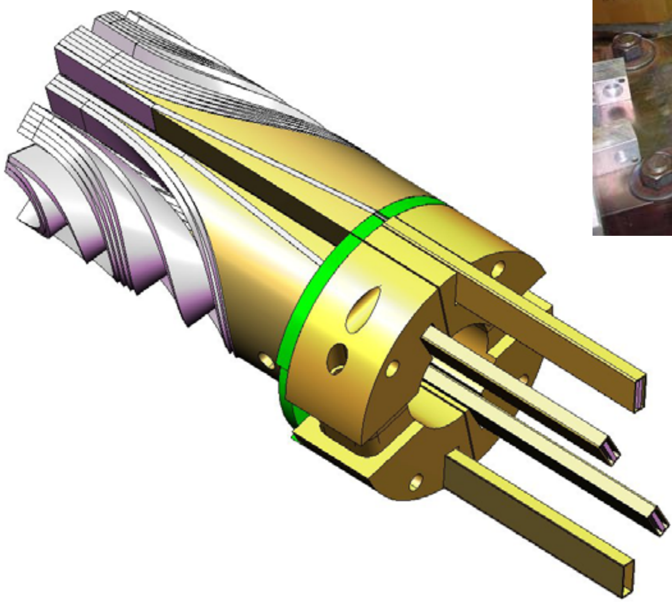
HFDA-04

# Reacted Coil

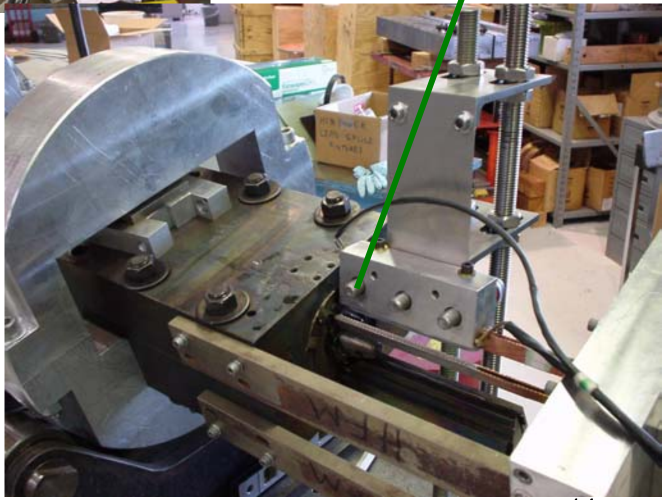

- Good bonding between the turns even after reaction
- Easy to handle

# HFDA-01 through HFDA-03 Splice Joints

- **Each $Nb_3Sn$ lead cable was spliced to two NbTi cables, one on each side in the vertical position**




Spring loaded



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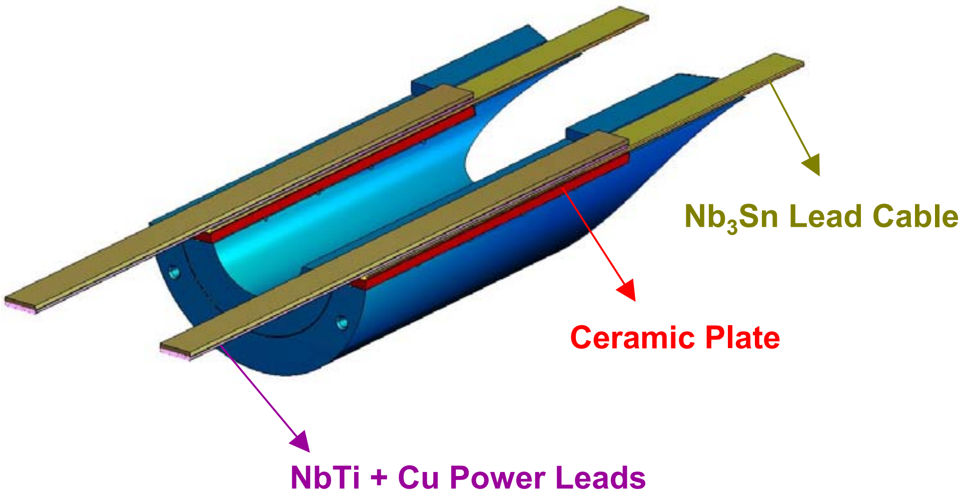
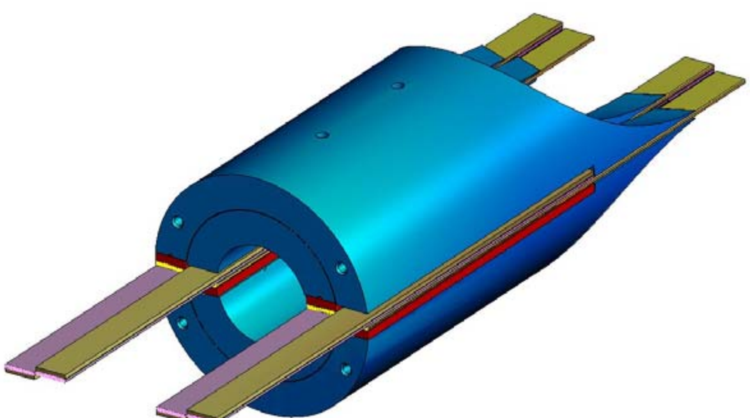
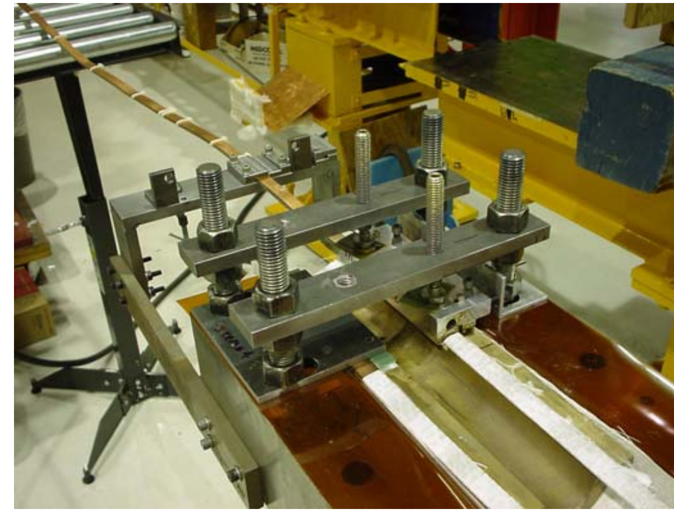
# HFDA-04 Splice Joints





**Each Lead cable was spliced separately in horizontal position with good support**

# Epoxy Impregnation

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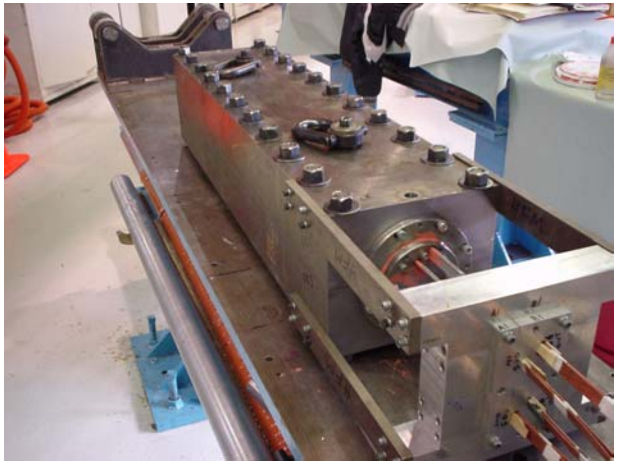
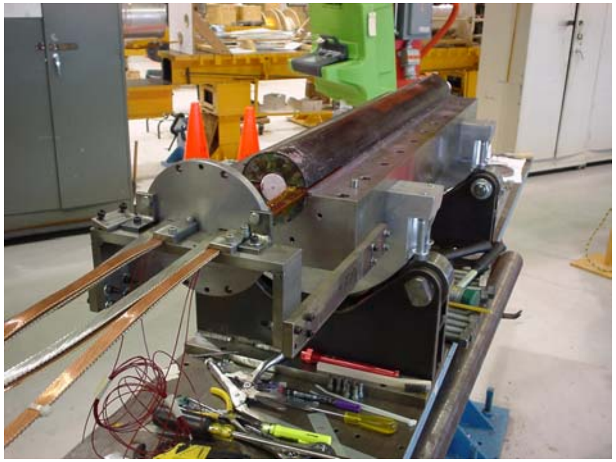
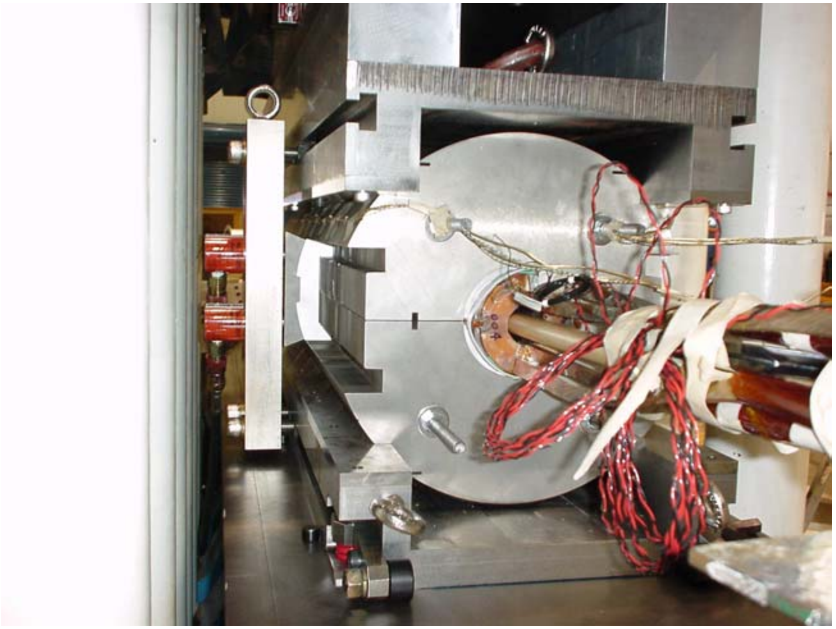
**HFDA-01 through HFDA-03: Both half coils were impregnated together**

**HFDA-04: The first half coil was impregnated separately and then the second half coil was impregnated along with the impregnated first half coil**



# Yoking




***Yoking provides about 30% of the required prestress to the coils***

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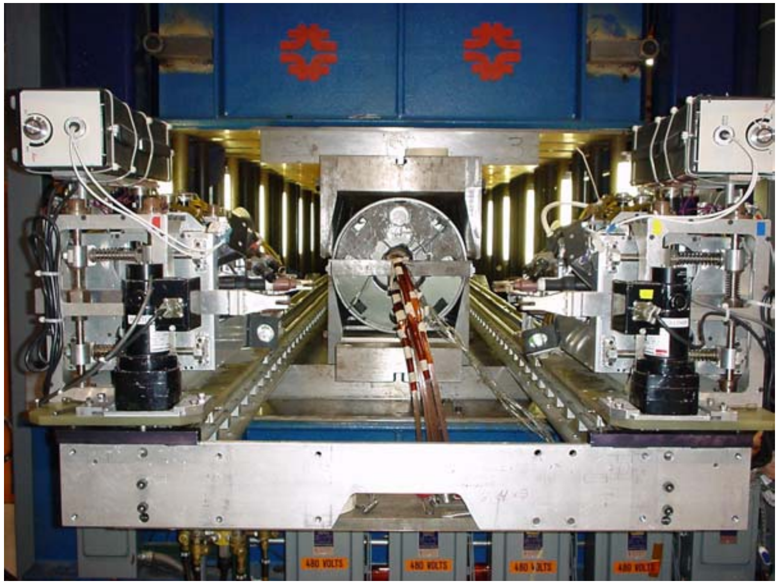
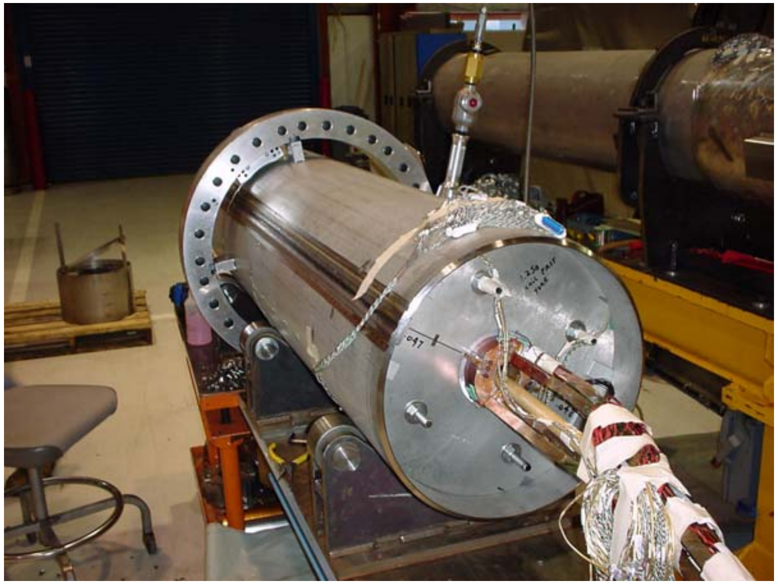
# Skinning

Magnet inside the welding press



Magnet after welding skin



*Weld Shrinkage provides rest of the pre-stress to the coils*

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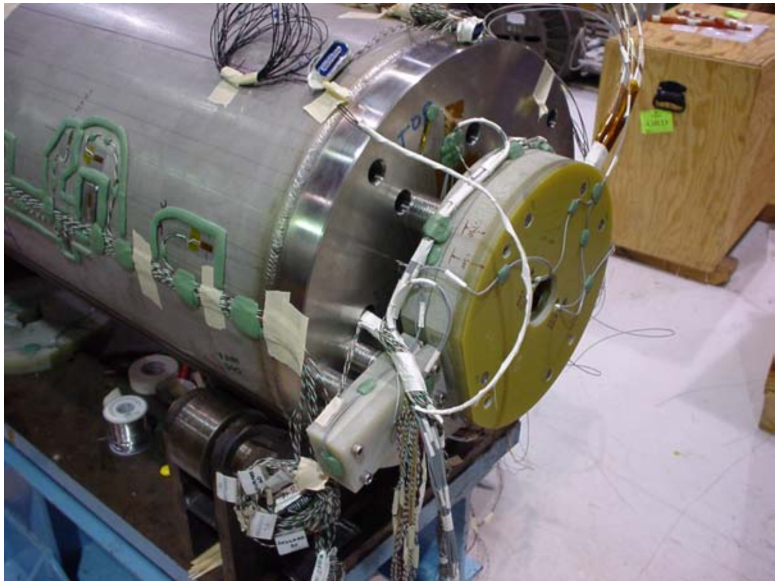
# Magnet Final Assembly

**Half Coil splicing assembly**



**Magnet ready to be tested**

# Measurements taken during Assembly

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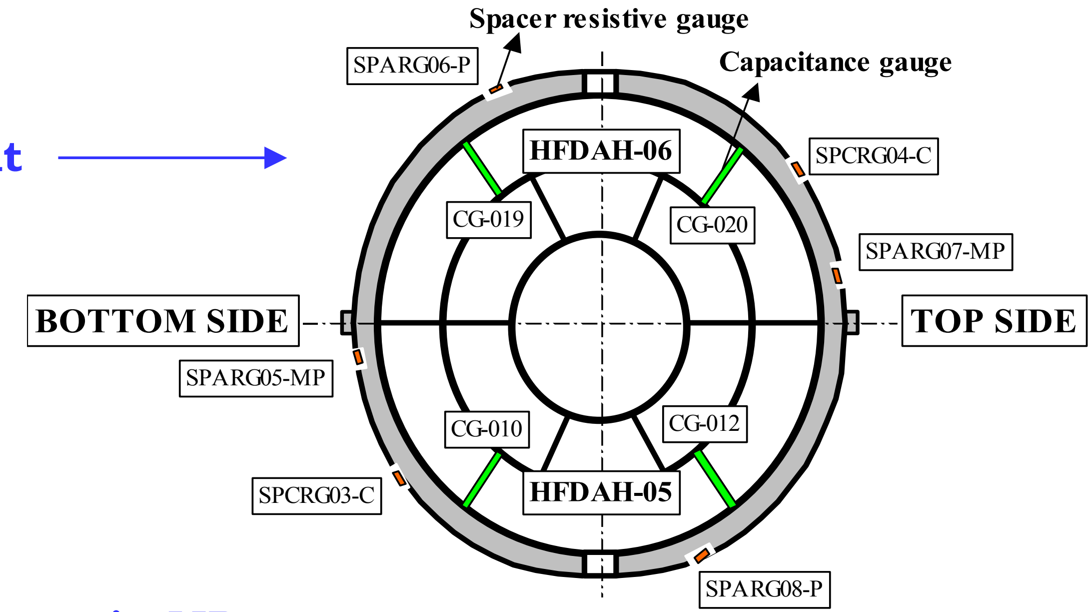
**Instrumentation Layout**




**Azimuthal Stress measurements in MPa**

| | Under Press | | During Clamping | | After Spring Back | | After Welding Skin | |
|---|---|---|---|---|---|---|---|---|
| | Coil | Spacer | Coil | Spacer | Coil | Spacer | Coil | Spacer |
| ANSYS | 50 | 160 | -- | -- | 20 | 108 | 60 | 165 |
| HFDA-02 | 85 | 213 | 94 | 223 | 30 | 115 | 55 | 159 |
| HFDA-03 | 76 | 153 | 80 | 157 | 24 | 97 | 54 | 120 |

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# Mirror Magnet Fabrication

- Mirror magnet configuration was chosen because of its fast turn-around time so that we can root-cause the poor quench performance observed in the previous dipole magnets, HFDA-02 through 04

- Three Mirror Magnets have been tested –
  - HFDA-03A: Half coil from HFDA-03 magnet was used
  - HFDA-03B: Splice Test
  - HFDM-02: New coil fabricated with pre-peg ceramic tape

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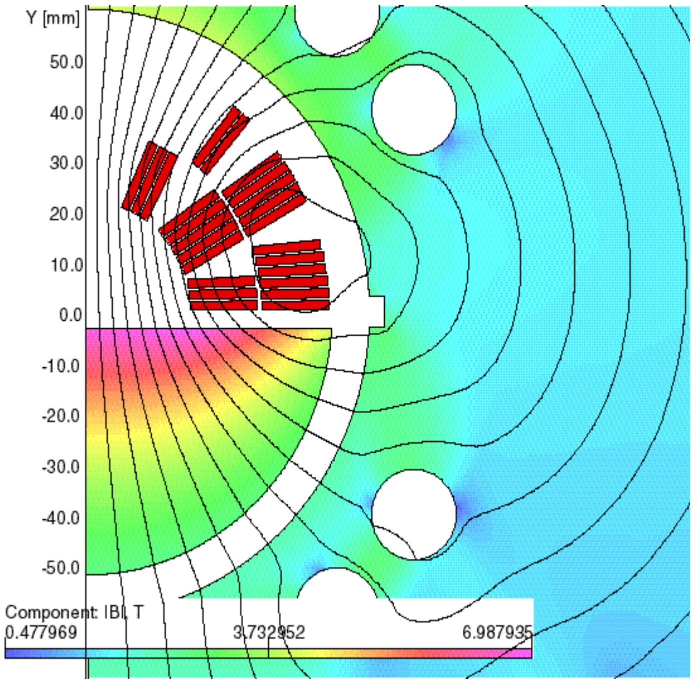
# Mirror Magnet: Magnetic Analysis




| Parameter | Value |
|---|---|
| Number of turns | 24 |
| Quench field in the bore center, T | 8.4 |
| Quench field in the conductor, T | 11.2 |
| Quench current, kA | 25 |
| Transfer function @ quench, T/kA | 0.334 |
| Stored energy @ quench, kJ/m | 146.3 |
| Inductance @ quench, mH/m | 0.467 |
| Forces per first coil quadrant @ 20 kA, MN/m | Fx = 1.73<br>Fy = -0.16 |

# Mirror Magnet: Mechanical Design

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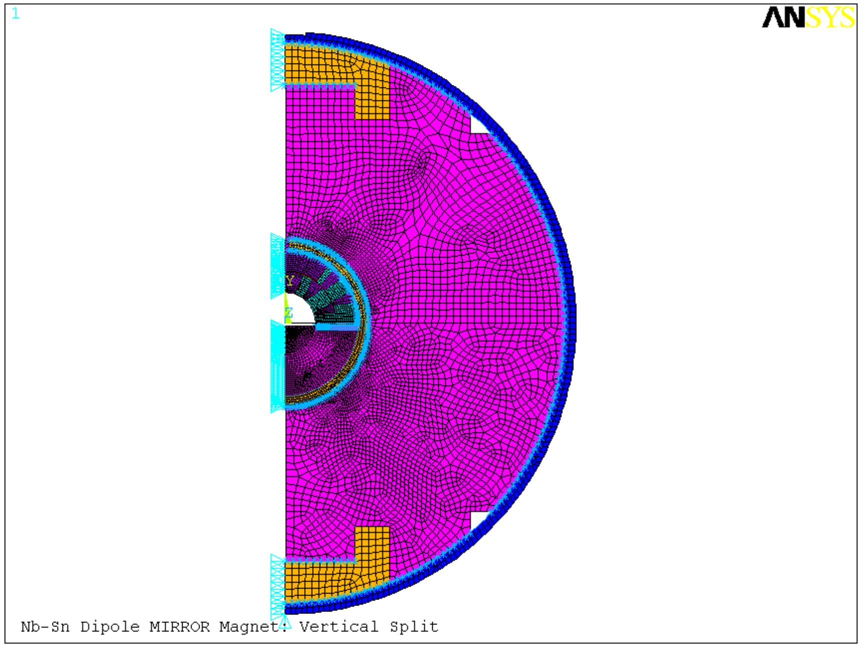
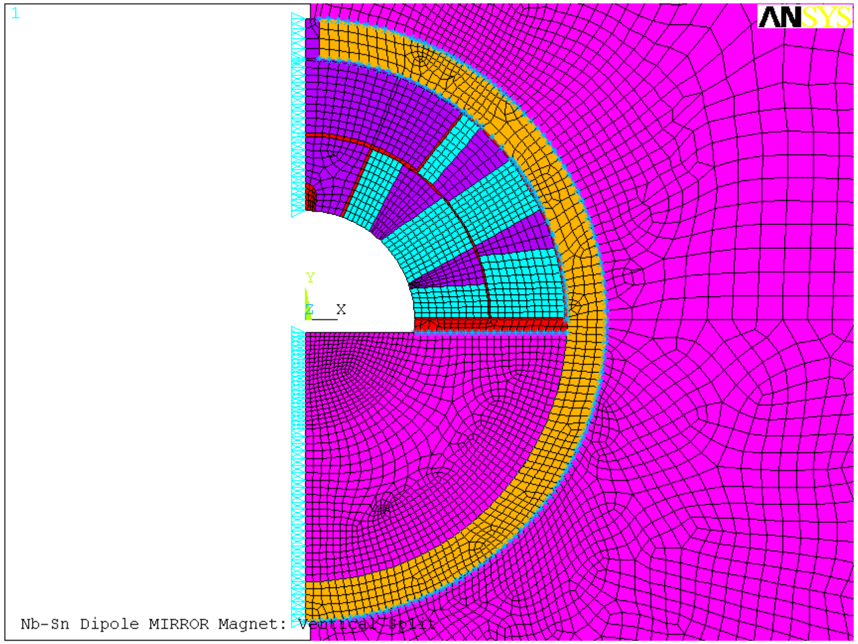
- ANSYS analysis was performed to check if the coil support structure designed for the dipole magnet would be sufficient for mirror configuration
  - A 3mm gap is left between the iron mirror and coil assembly for the splice joints. In the straight section this gap was filled with G-10 shims and epoxy

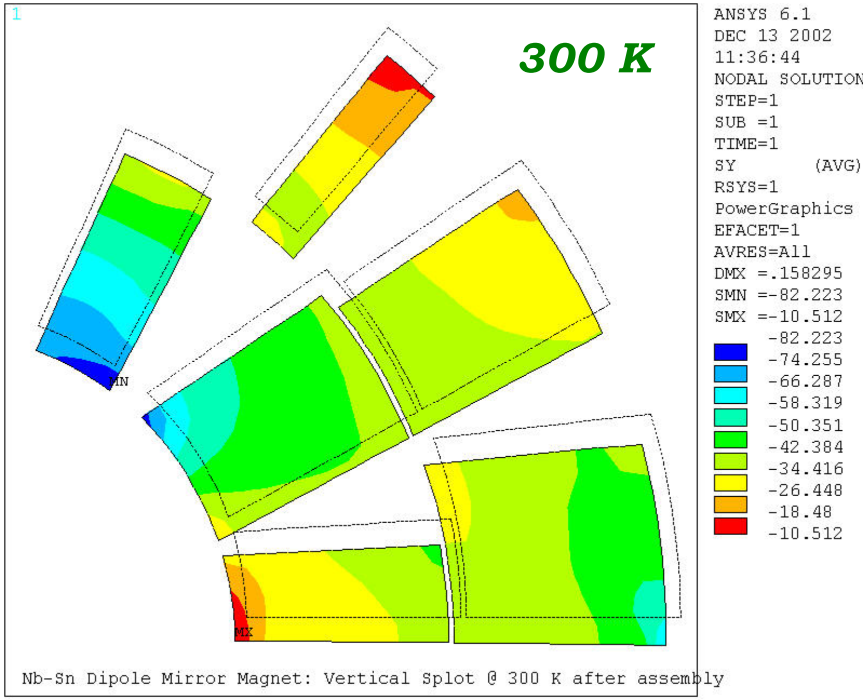


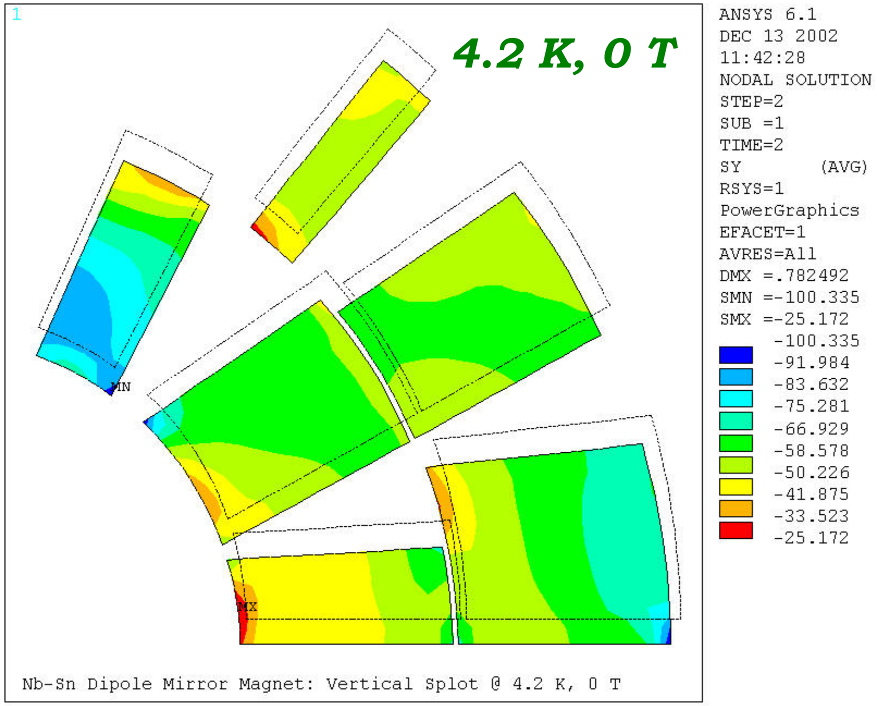



# Mirror Magnet: Mechanical Design

## ❖ Azimuthal Stress Distribution in the Coil

- **The peak stress in the coil at room temperature after assembly is 82 MPa in the inner layer pole region. On cool down the maximum stress increases to about 100 MPa**

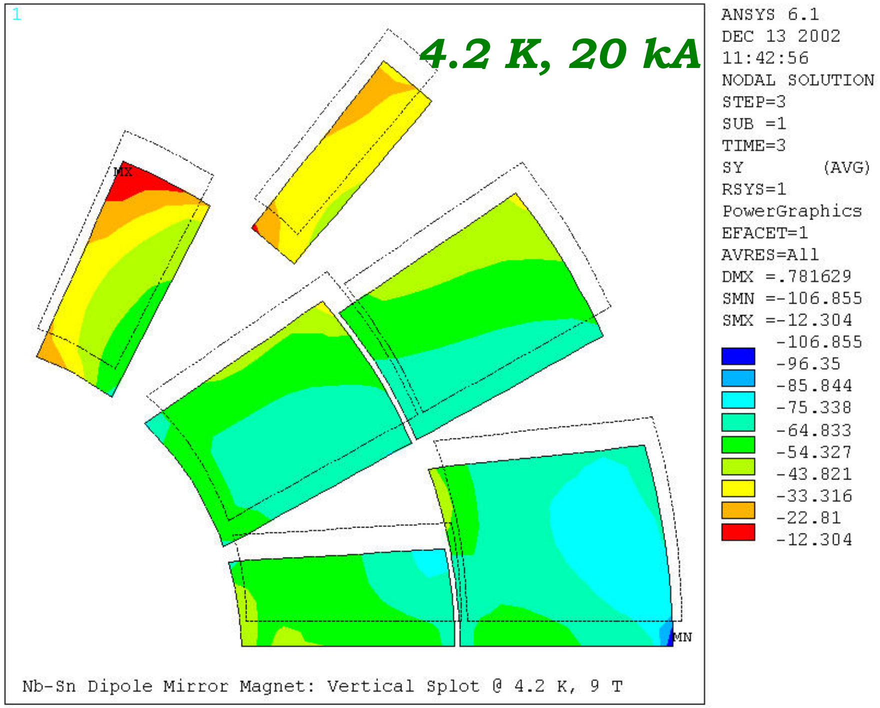


# Mirror Magnet: Mechanical Design

## ❖ Azimuthal stress distribution in the coil (contd..)

- **Due to Lorentz forces, the stress in the pole region decreases whereas the stress in the mid-plane increases. Note that the maximum stress is in the outer layer which is in a low field region**



# HFDA-03A

- Half coil from HFDA-03 dipole magnet was picked to fabricate the first mirror magnet with several additions
- Two new sets of splice joints and various instrumentation were added to investigate the following issues
  - ***Current Sharing***: Both lead end and return end splice joints would improve current sharing in the coil
  - ***Splice Joints***: The new splice joints at lead end could be used to bypass the old splice joints to check if the poor quench performance observed in HFDA-03 was due to the result of conductor damage during splicing operation
  - ***Conductor Damage***: Spot heaters and temperature sensors were installed to measure the local behavior of the conductor

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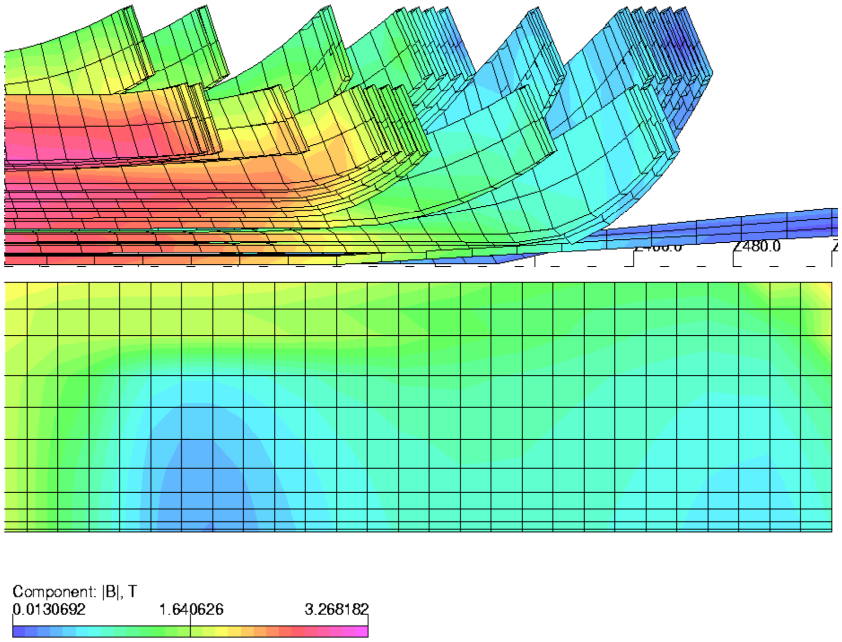
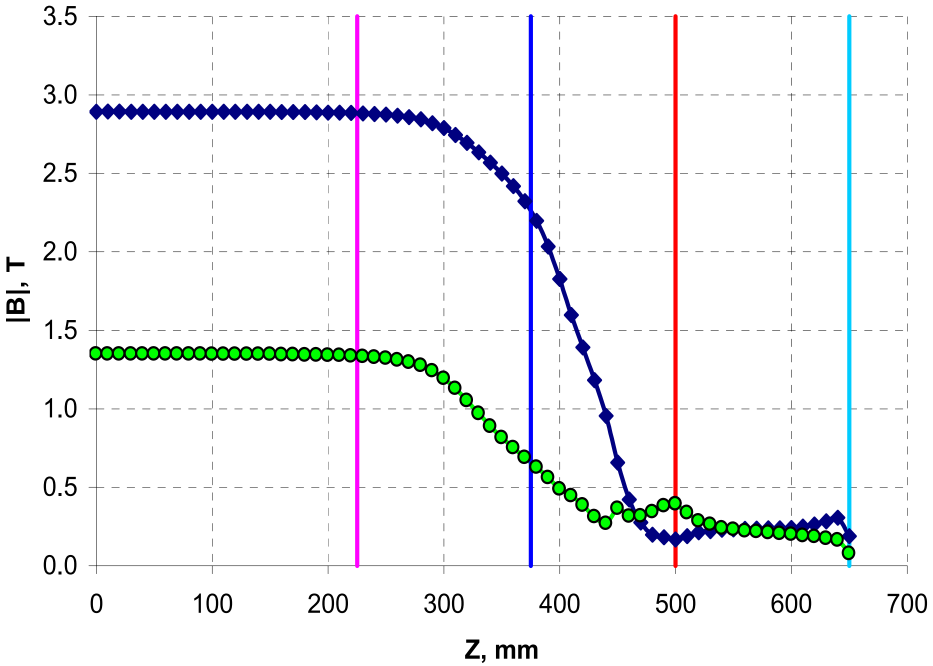
# HFDA-03A: Magnetic Analysis

- **OPERA 3D model was created to estimate the magnetic fields near the new splice joints**




*Field in Y-Z Coil Cross-section at 6 kA*




*Peak field distribution along the lead cables at 6 kA*

# HFDA-03A: Splice Joints

- Mid-plane insulation was carefully removed before splicing NbTi lead cables both at lead end and return end

# HFDA-03A: Instrumentation

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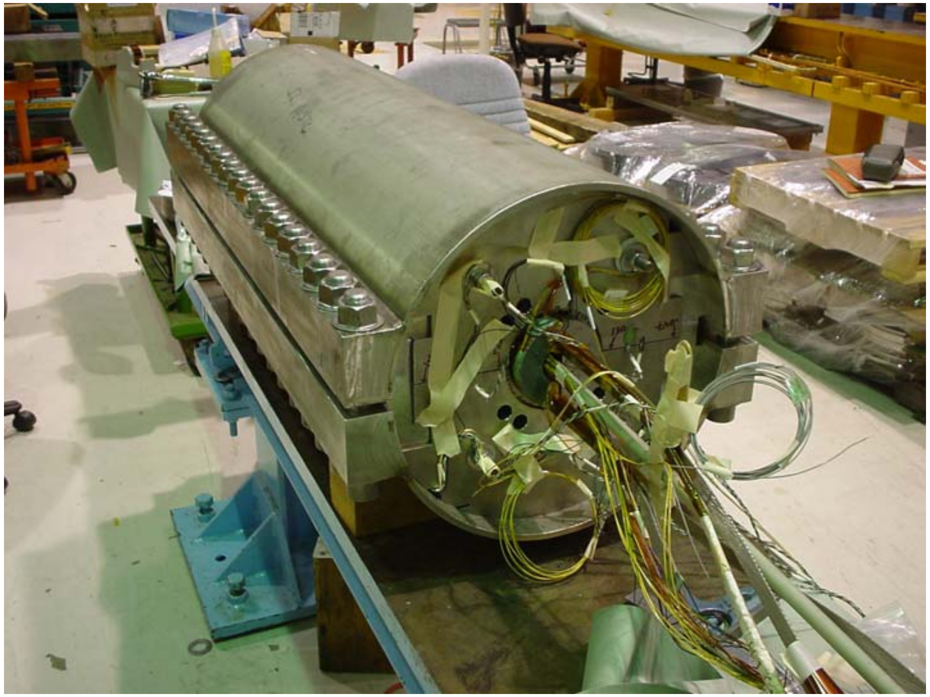
- **Several voltage taps, spot heaters and temperature sensors were installed to study the quench behavior**

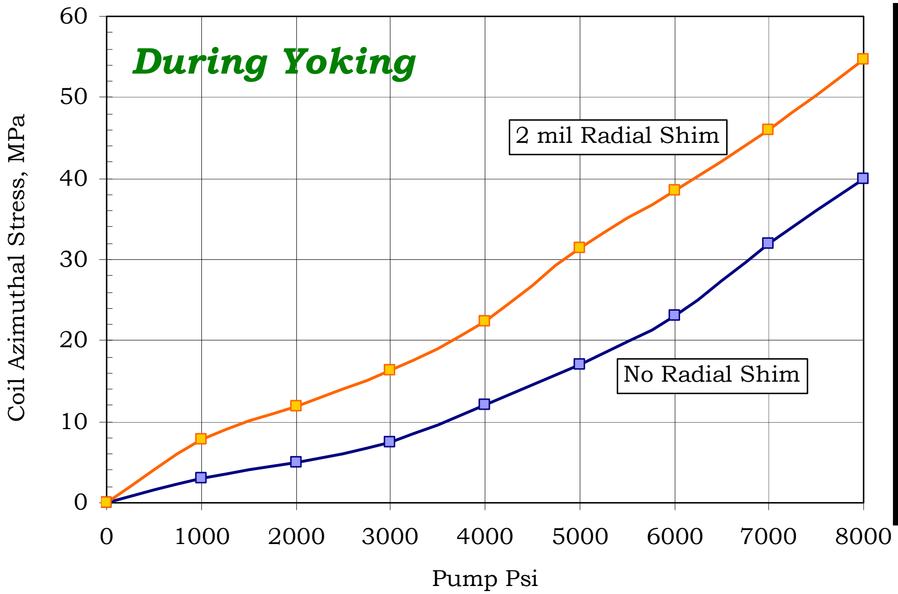
# HFDA-03A: Assembly

- The assembly procedure was similar to that of the previous dipole magnets except that we replaced welded skins with a bolted structure



# HFDA-03A: Assembly Data

- **The coil and spacer azimuthal stress was monitored at all stages of assembly**
  - **Two mil radial shim between coil and the spacer was added to increase the contribution to coil pre-stress during yoking, thus reducing the amount of torquing on the bolted skin**

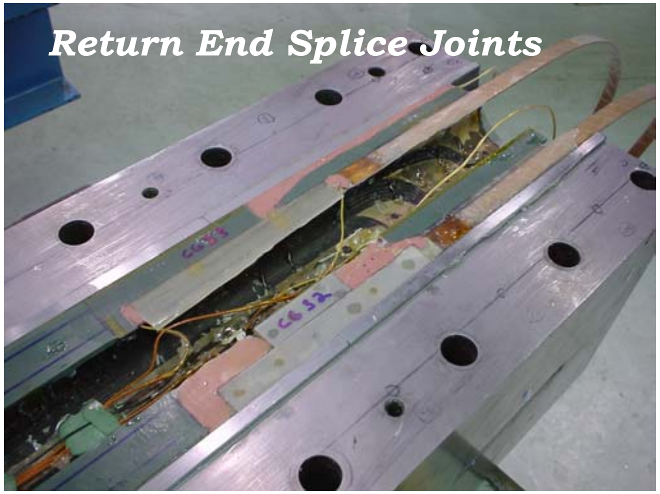


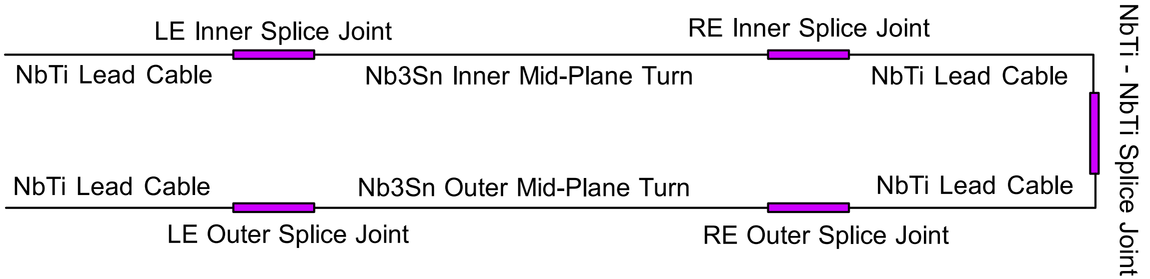

| | Yoking / Clamping | After Spring Back | After Skinning |
|---|---|---|---|
| Coil Outer Layer Pole, MPa | 54 (45)* | 17 (25) | 28 (26) |
| Spacer Pole (Coil Side), MPa | 68 (90) | 43 (50) | 58 (119) |
| Spacer Pole (Mirror Side), MPa | 110 (105) | 68 (58) | 79 (110) |
| Spacer Mid-Plane, MPa | 33 (35) | 37 (33) | 40 (86) |

** The data in the brackets are from ANSYS analysis*

# HFDA-03B: Splice Test

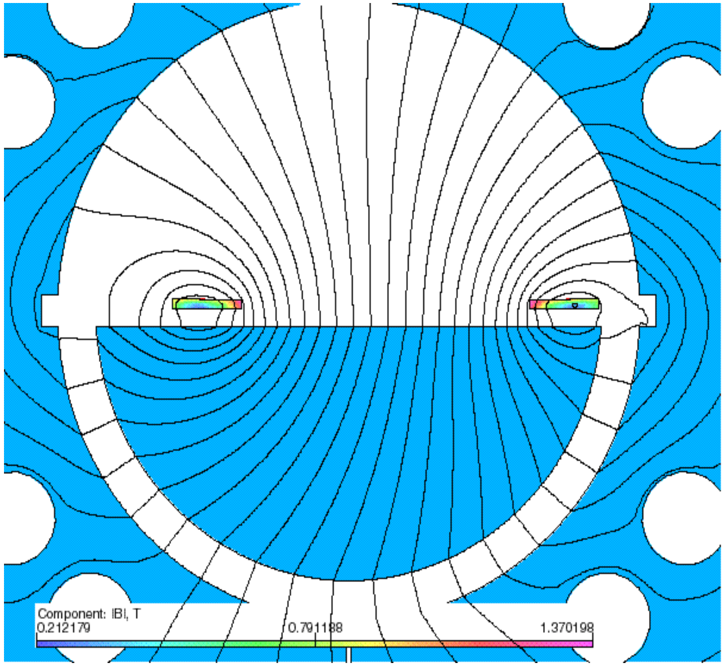
- The goal was to test the splice joints in a configuration similar to that in a magnet
- The return end shunts were removed from HFDA-03A coil and new NbTi lead cables were spliced
  - The cable next to the return end splice joints was cut to separate the mid-plane cable from the rest of the turns
  - This configuration would allow us to test the four splices in series or the two splices on the inner or outer layer separately

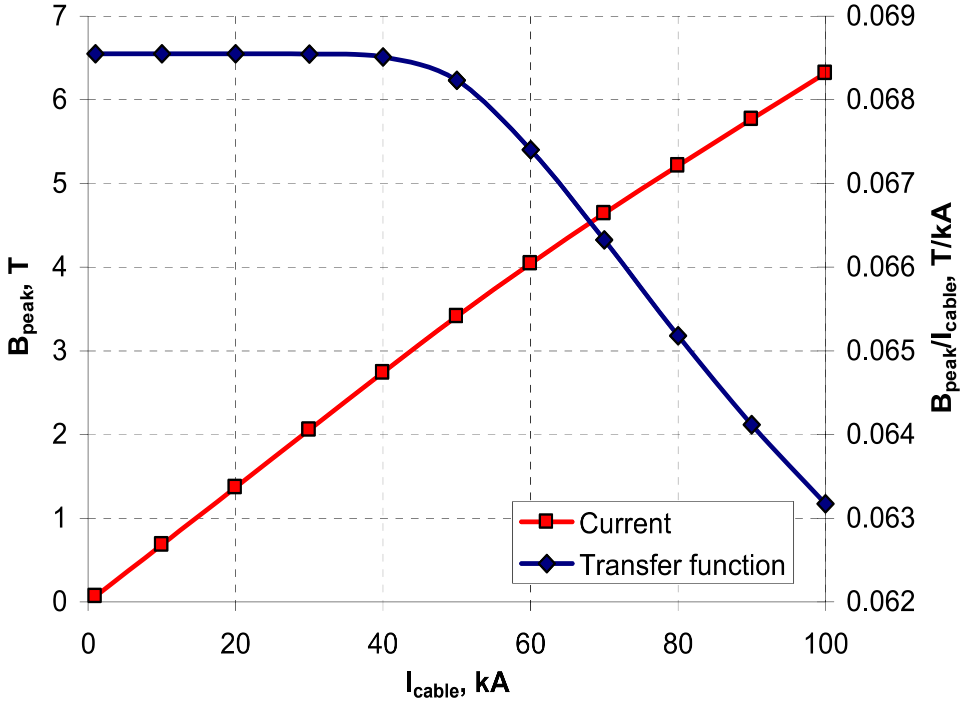


# HFDA-03B: Magnetic Analysis






- At the power supply limit of 20 kA, the maximum field in the cable is about 1.37 T
- The peak field is at the inner surface of the outer-layer cable. The maximum field in the inner-layer cable is about 3% less

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# HFDA-03B: Mechanical Assembly Data

| | Inner Midplane | | Outer Midplane | | Spacer: Coil Side | | Spacer: Mirror Side | | Spacer: Midplane | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Data | Ansys | Data | Ansys | Data | Ansys | Data | Ansys | Data | Ansys |
| Yoking /Clamping | 54.6 | 40 | 59.7 | 50 | 100 | 90 | 112 | 103 | 65 | 70 |
| After Spring Back | 27.1 | 22 | 23.9 | 35 | 49 | 80 | 65 | 72 | 53 | 50 |
| After Skinning | *17.7* | 32 | 50.8 | 40 | 60 | 90 | 70 | 75 | 54 | 65 |

*Units = MPa*

# HFDM-01 & HFDM-02 Fabrication

- **New features were introduced during coil fabrication to improve current sharing between the strands**
  - **Steps were taken to reduce binder penetration between the strands in the cable and still keep the coil curing process**
    - **Copper wrap between cable and ceramic insulation (HFDM-01)**
    - **Pre-peg ceramic tape (HFDM-02)**
  - **Coils were reacted under pressure similar to that of other shell-type and racetrack coils made elsewhere**
- **The flatness and stress distributions along the length of the coils were measured and compared with the tooling shape and necessary modifications were implemented**
- **Horizontal split iron yoke design was analyzed with a goal to reduce the pre-stress in the coil during assembly to around 50-75 MPa**

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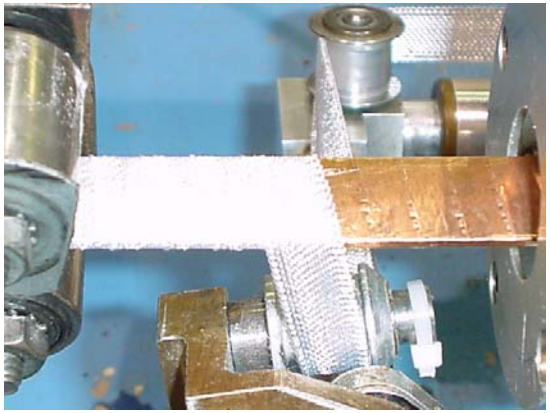
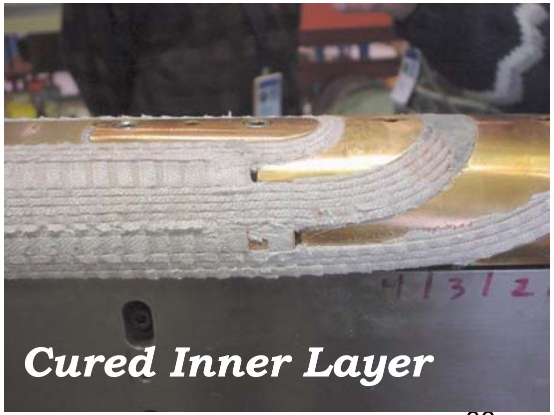
# HFDM-01 Coil Fabrication

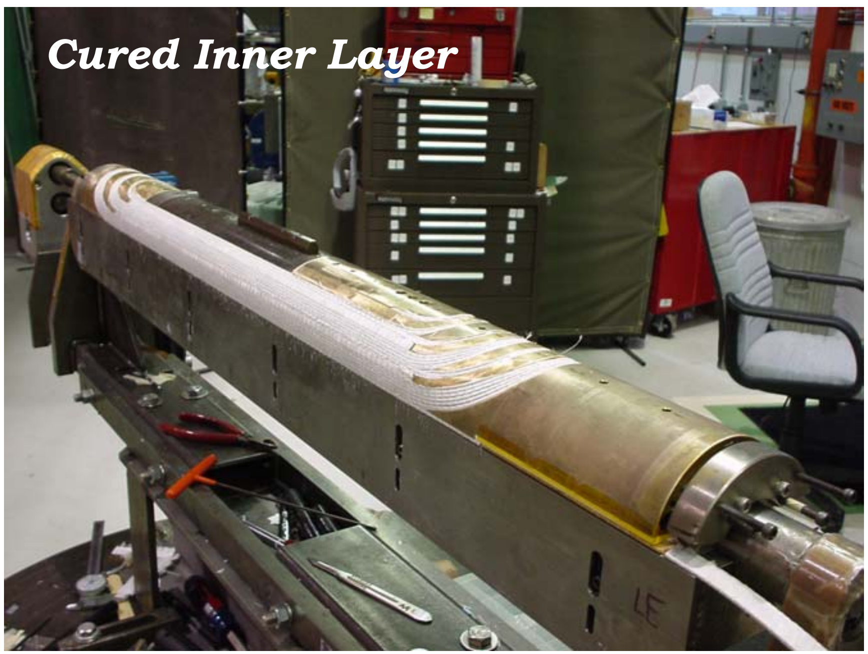
- Several alternate methods of wrapping copper and ceramic tape were investigated to prevent binder penetration
  - 25 to 50% overlap copper tape prevented most of the binder from reaching the cable
- HFDM-01 cable was wrapped with 25% overlap copper tape before insulating with 40% overlap ceramic tape
  - The ceramic tape was not reinforced with the liquid binder during the insulation stage. However, after winding the coil, binder was applied to the turns and cured.
  - This approach demonstrated acceptable results, but with less degree of bonding between the turns

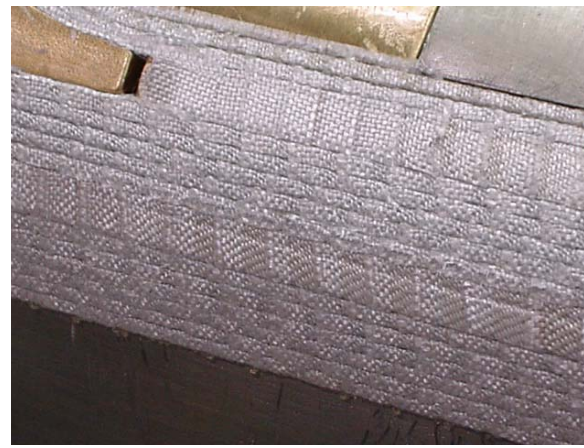





# HFDM-02 Coil Fabrication

- **Upon Fermilab's suggestion, CTD developed an experimental pre-preg form of ceramic tape that would reduce the binder penetration between the strands in the cable**



After Curing

After Reaction

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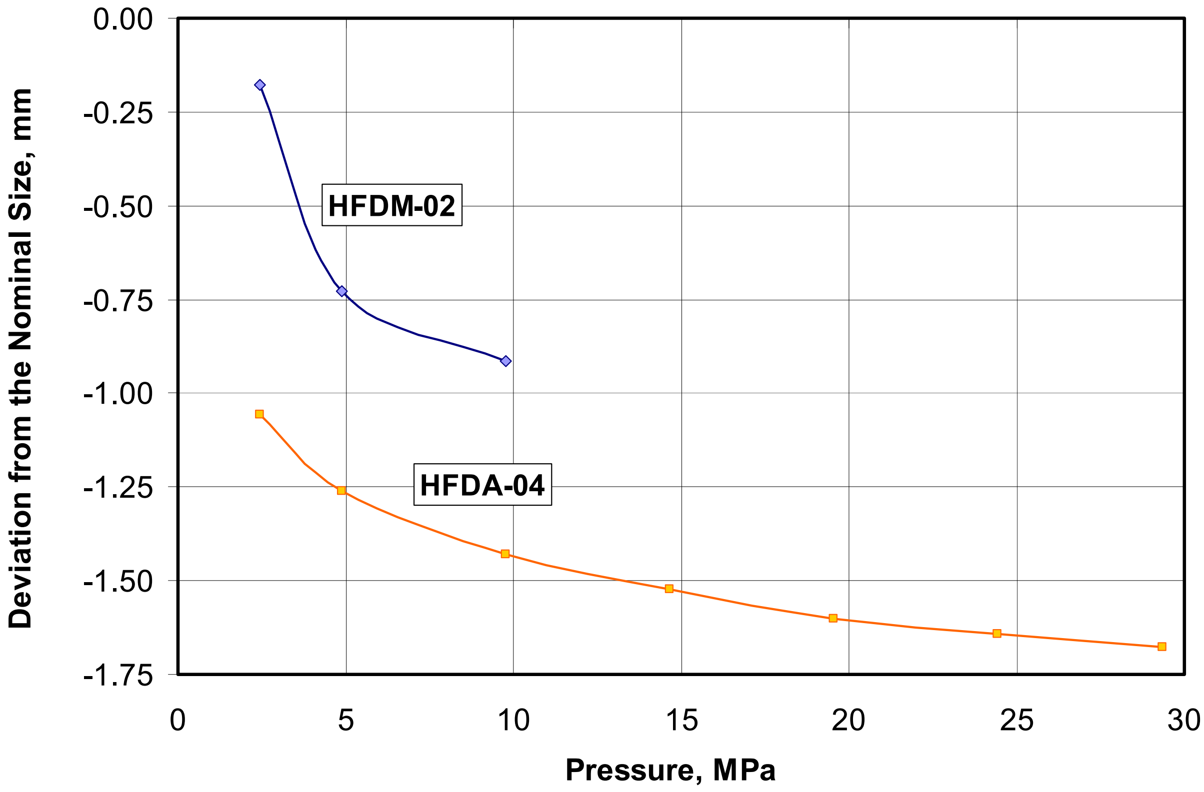
# HFDM-02 Coil Size Measurements

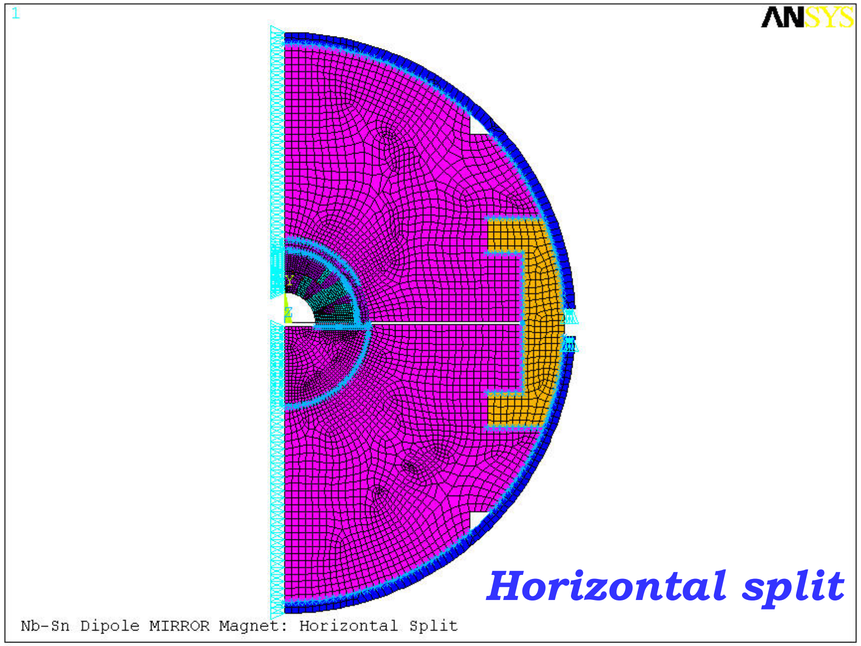


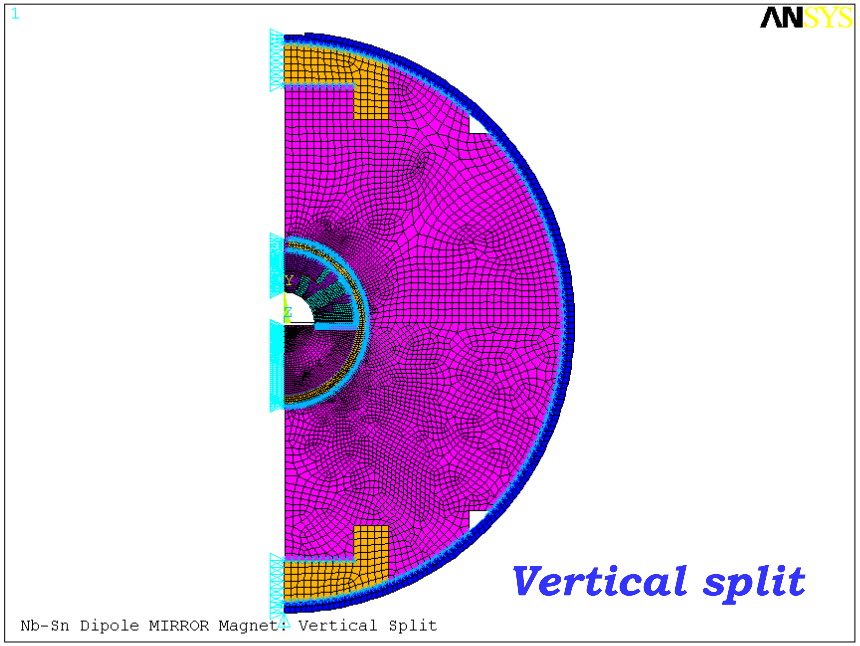
# HFDM-02 Coil Reaction/Impregnation

- **Coil reaction, splicing and epoxy impregnation were similar to HFDA-04 half coil with the following exceptions**
  - **Reaction:**
    - **The azimuthal size of HFDM-02 half coil was shimmed up to the nominal so that reaction occurs under pressure**
    - **The mandrel in the coil bore was removed during reaction to allow for cable expansion (if any) in the radial direction**
    - **The coil was free to expand in the longitudinal direction**
  - **Splice Joints:**
    - **NbTi cables were inserted on either side of the $Nb_3Sn$ lead cable during splicing operation (in HFDA-04 we had NbTi + Cu lead cables spliced from the top)**
    - **Holes were drilled in the end-saddles to provide better cooling for splice joints**
  - **Impregnation:**
    - **Impregnation tooling was modified to reduce the bowing observed in all the previous coils**

# HFDM-02 Assembly Process

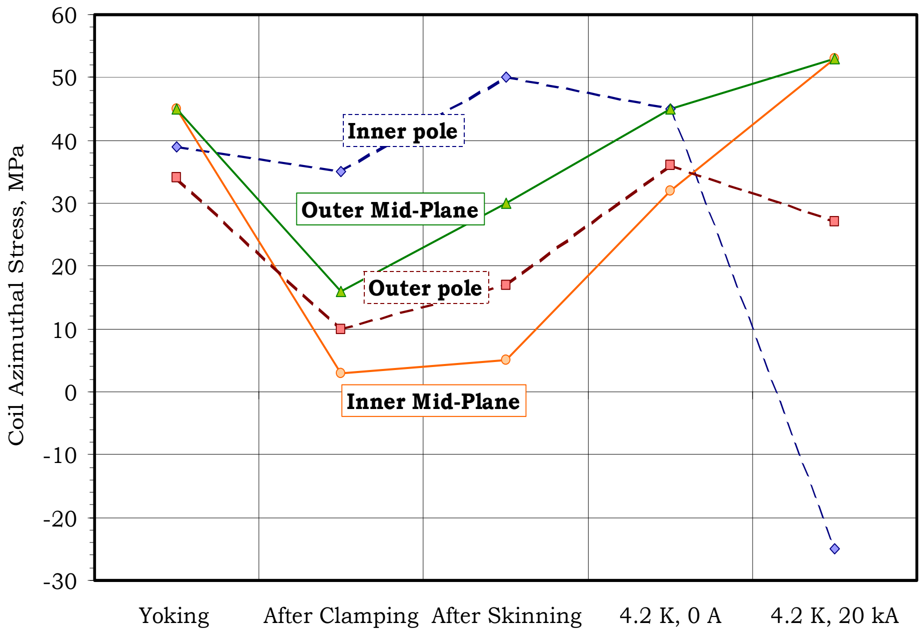
- **Horizontal split yoke design was chosen for the following reasons –**
  - **It would simplify the assembly process for mirror magnets**
  - **The pre-stress in the coil can be easily altered by changing the amount of shim in the mid-plane**

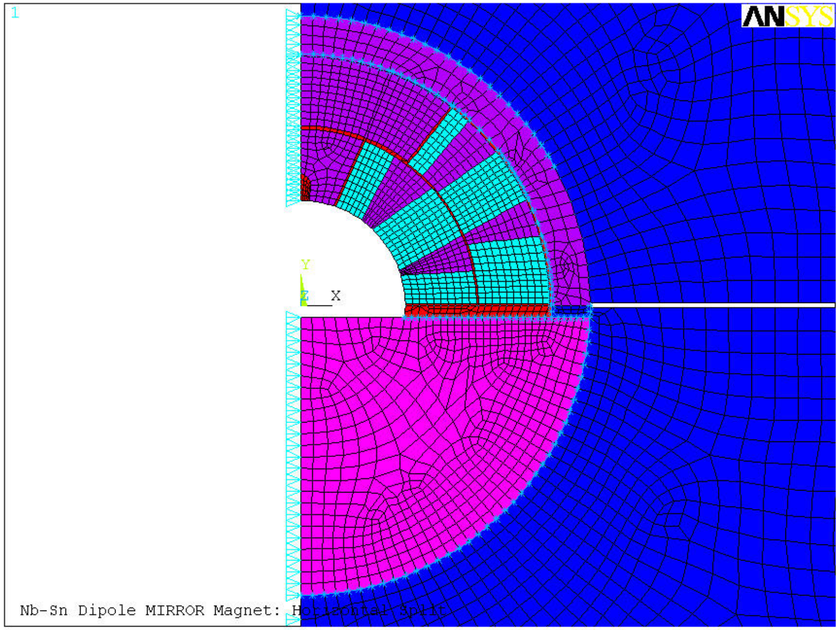


# Horizontal Split: Mechanical Analysis

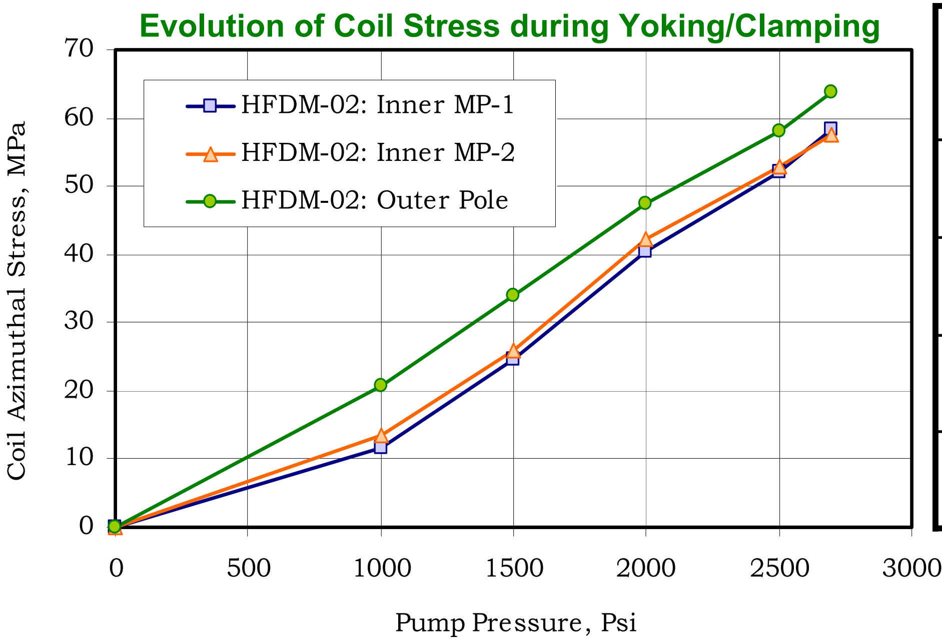
- **The mid-plane and radial interference was adjusted to get the desired pre-stress distribution in the coil**
  - **The plot shows the average stress in coil at different locations for 0.10 mm of mid-plane interface and 0.05 mm of radial interference**



# HFDM-02: Final Assembly

- **The strategy was to assemble the coil with low pre-stress and if needed increase it in the subsequent thermal cycles**
  - **Capacitance gauges were used to measure the stresses in the Inner-layer mid-plane and outer-layer pole region. The stresses in the spacer were measured using resistive gauges**




| | Yoking / Clamping | After Spring Back | After Skinning |
|---|---|---|---|
| Coil Inner Layer Mid-Plane, MPa | 41 (50)* | 27 (37) | 35 (20) |
| Coil Outer Layer Pole, MPa | 55 (48) | 35 (41) | 50 (37) |
| Spacer Pole, MPa | 64 (43) | 54 (20) | 60 (50) |
| Spacer Mid-plane, MPa | 4 (25) | 2 (32) | 2 (44) |

* The data in the brackets are from ANSYS analysis

# Current Status: HFDM-03 and beyond

- Winding of new half coil with PIT strand will begin on August 11th
- HFDM-03 mirror magnet fabrication is expected to finish by the middle November (the delay is due to winding and curing of a practice coil currently underway to test the new reaction and impregnation tooling)
- End-part design for the new 0.7 mm strand OST-MJR coil cross-section is underway. Expected to have the parts fabricated by the end of November